NASA CR-72123
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FINAL REPORT

RESISTOJET RESEARCH AND DEVELOPMENT - PHASE II

Supplement No. 1

DESIGN, DEVELOPMENT AND FABRICATION OF AN AMMONIA-FUELED RESISTOJET THRUSTOR SYSTEM

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

December 1966

Contract NAS3-5908

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
Electric Propulsion Office
Henry Hunczak

AVCO MISSILES, SPACE AND ELECTRONICS GROUP
MISSILE AND SPACE SYSTEMS DIVISION
RESEARCH AND TECHNOLOGY LABORATORIES
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I. INTRODUCTION

A. PROGRAM OBJECTIVES

The basic objective of this program was to develop two complete 0.54 ± 10 percent millipound, ammonia-fueled resistojet thrustor systems. The thrustor system was to be suitable for spacecraft inversion maneuvers, and was defined to include two thrustors and two solenoid flow control valves, one zero-g, ammonia-propellant feed system, and appropriate power and signal-conditioning equipment to be compatible with on-board power and telemetry equipment. The total system power requirement was to be less than 10 watts, the total impulse capability a minimum of 100 lb-sec, and a specific impulse in excess of 120 seconds. Finally, the resistojet thrustor systems were to be of flight design suitable for meeting appropriate environmental test specifications.

B. PROGRAM ORGANIZATION

This program originated from the Electric Propulsion Office of the NASA Lewis Research Center. Mr. Henry Hunczak was Project Manager for NASA Lewis. The Project Director at Avco/SSD was Dr. R. R. John. The other participants in this program, and their principal areas of contribution, were: Mr. R. Cybulski, Mr. W. Davis, Mr. R. Ingemi, and Mr. K, Pugmire, Thrustor and Propellant Feed System Development; Mr. J. Olbrych, Power and Signal Conditioning Design and Development.

C. PROGRAM SUMMARY

Two complete ammonia-fueled resistojet thrustor systems were delivered to NASA Lewis. The individual resistojet engines operate at thrust levels of 0.54 millipound and at specific impulse levels in excess of 120 seconds. The total system input power is less than 8.5 watts; the total propulsion system weight (filled) is 6.1 pounds, which included 0.9 pound of propellant.

The resistojet thrustor system is compatible with 24-vdc input power. The signal-conditioning equipment includes provision for recording the clockwise and counterclockwise valve-on signals, the clockwise and counterclockwise heater-on signals, and the plenum pressure. The basic input signals are clockwise-thrustor-on and counterclockwise thrustor-on. The required operational system life of greater than 50 hours has been demonstrated in the laboratory.

II. SUBSYSTEM COMPONENT DESIGN AND DEVELOPMENT

A. BASIC RESISTOJET THRUSTOR SYSTEM

The basic ammonia-fueled resistojet thrustor system is shown schematically in Figure 1, and a photograph of the unit is shown in Figure 2. Referring to Figure 1, the critical features of the system are: the fast heat-up thrustors (item 5); the thrustor solenoid valves (item 4), which admit gas to the individual engines; the power and signal-conditioning module (item 7), which matches the spacecraft telemetry and power systems with the corresponding requirements for the thrustor system; and the zero-g, propellant-feed system (items 1 and 3) which prepares the liquid ammonia for operation in the individual engines. The individual subsystems are discussed below.

The overall system weighs 6.1 pounds full and 5.2 pounds empty. The unit, with the exception of the thrustors, which will be located on the spacecraft surface, can be contained in a cylinder 4 inches in diameter and 10 inches long.

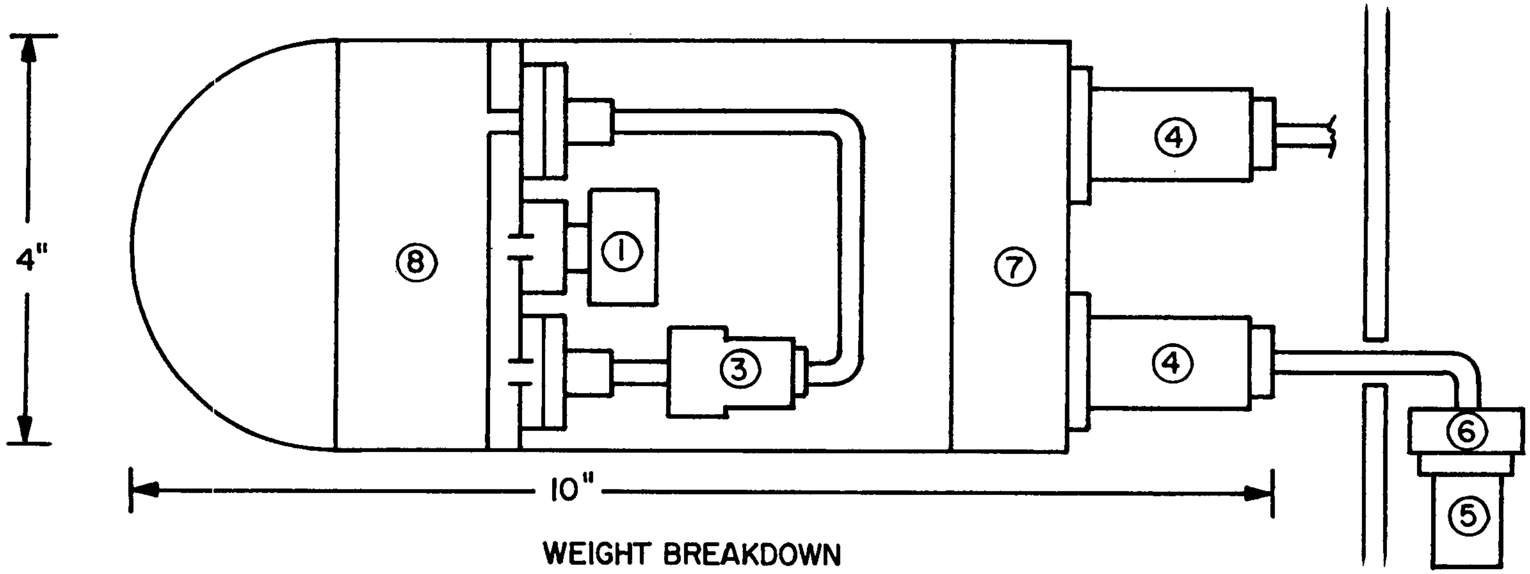
B. RESISTOJET THRUSTOR DEVELOPMENT

1. Thrustor Design

The basic thrustor design (ref. 1) used on the ammonia-fueled resistojet thrustor system is shown in Figure 3. A photograph of the unit is shown in Figure 4. Briefly the resistojet thrustor consists of a central single-pass heat exchanger and exit nozzle. The heater tube is, in turn, surrounded by a support tube. The current connections are located at the cold end of the support tube. The ammonia propellant is heated as it passes through the heater tube, and the thermal energy is converted into kinetic energy during expansion through the exit nozzle.

2. Thrustor Performance

A diagram of the stainless steel heater-nozzle element used for the subject program is shown in Figure 5. Typical performance data are shown in Figures 6 through 8. Figure 6 indicates ammonia flow rate as a function of chamber pressure for a fixed input power of 4 watts. As the plenum pressure is increased, there is a corresponding increase in ammonia flow rate. Figure 7 shows the measured engine thrust (ref. 1) as a function of chamber pressure, again at 4 watts input power. Finally, Figure 8 shows measured specific impulse as a function of chamber pressure. The mean specific impulse is about 150 seconds at 4 watts input power.



WEIGHT BREAKDOWN

① PRESSURE SWITCH – 0.08 lbs.
② FILL VALVE – 0.06 lbs.
③ SUPPLY VALVE – 0.10 lbs.
④ CONTROL VALVES – 0.20 lbs.
2ea. 0.10 lbs
⑤ ENGINE-HEATER – 0.12 lbs.
2ea. 0.06 lbs.

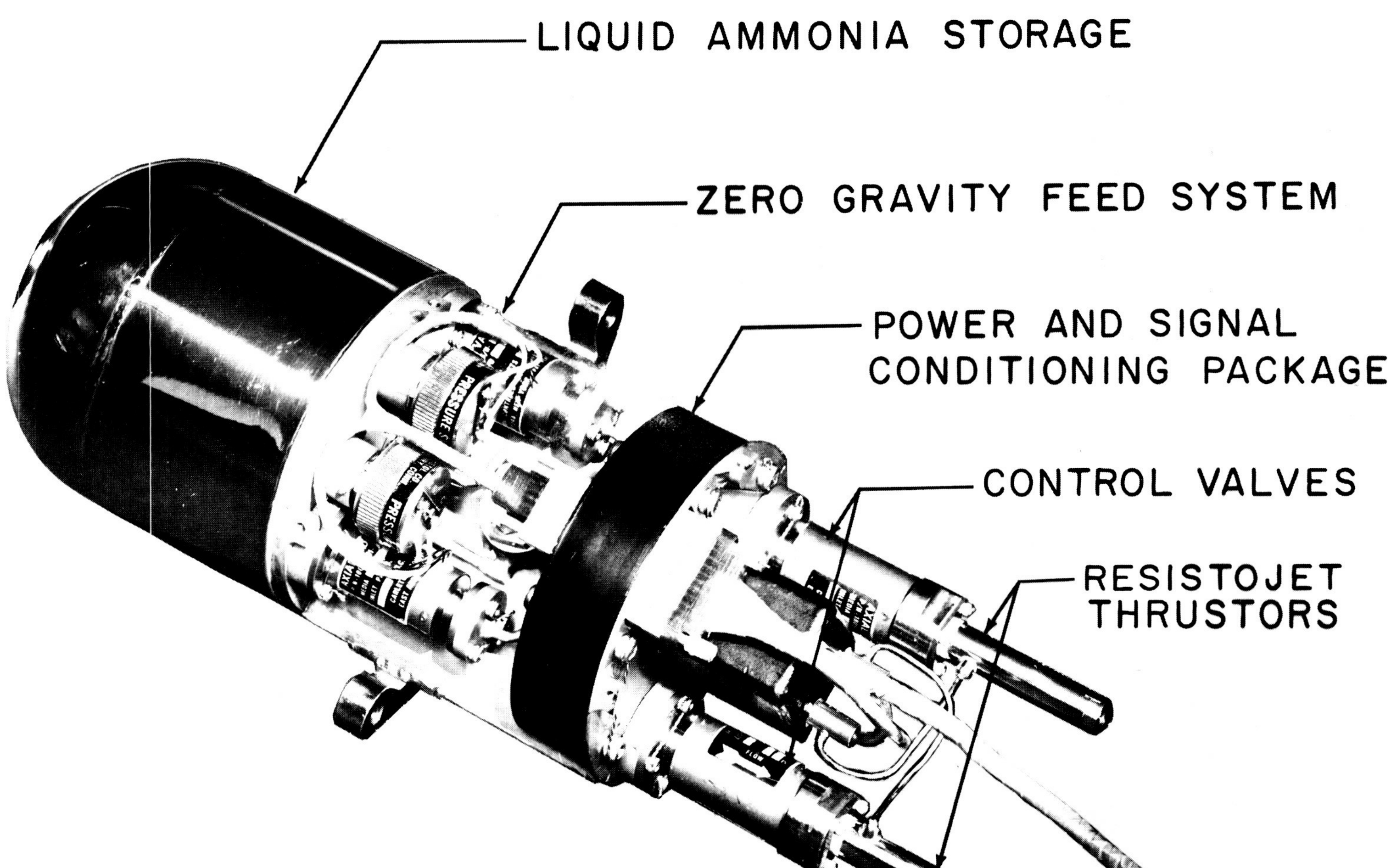
⑥ TRANSFORMER – 1.00 lbs. 2 ea. 0.50 lbs.
⑦ POWER PACKAGE – 0.34 lb
⑧ STRUCTURE / TANKAGE – 3.30 lbs.

TOTAL WEIGHT 5.2 lbs. (EMPTY)

TOTAL WEIGHT 6.1 lbs. (FULL)

26-1754

Figure 1 BASIC AMMONIA-FUELED RESISTOJET SATELLITE INVERSION SYSTEM



PACKAGE WEIGHT	6 LBS (FULL)
TOTAL POWER INPUT	7.5 WATTS
TOTAL IMPULSE CAPABILITY	100 LB-SEC
THRUST LEVEL	500×10^{-6} LBS
SPECIFIC IMPULSE	150 SECONDS

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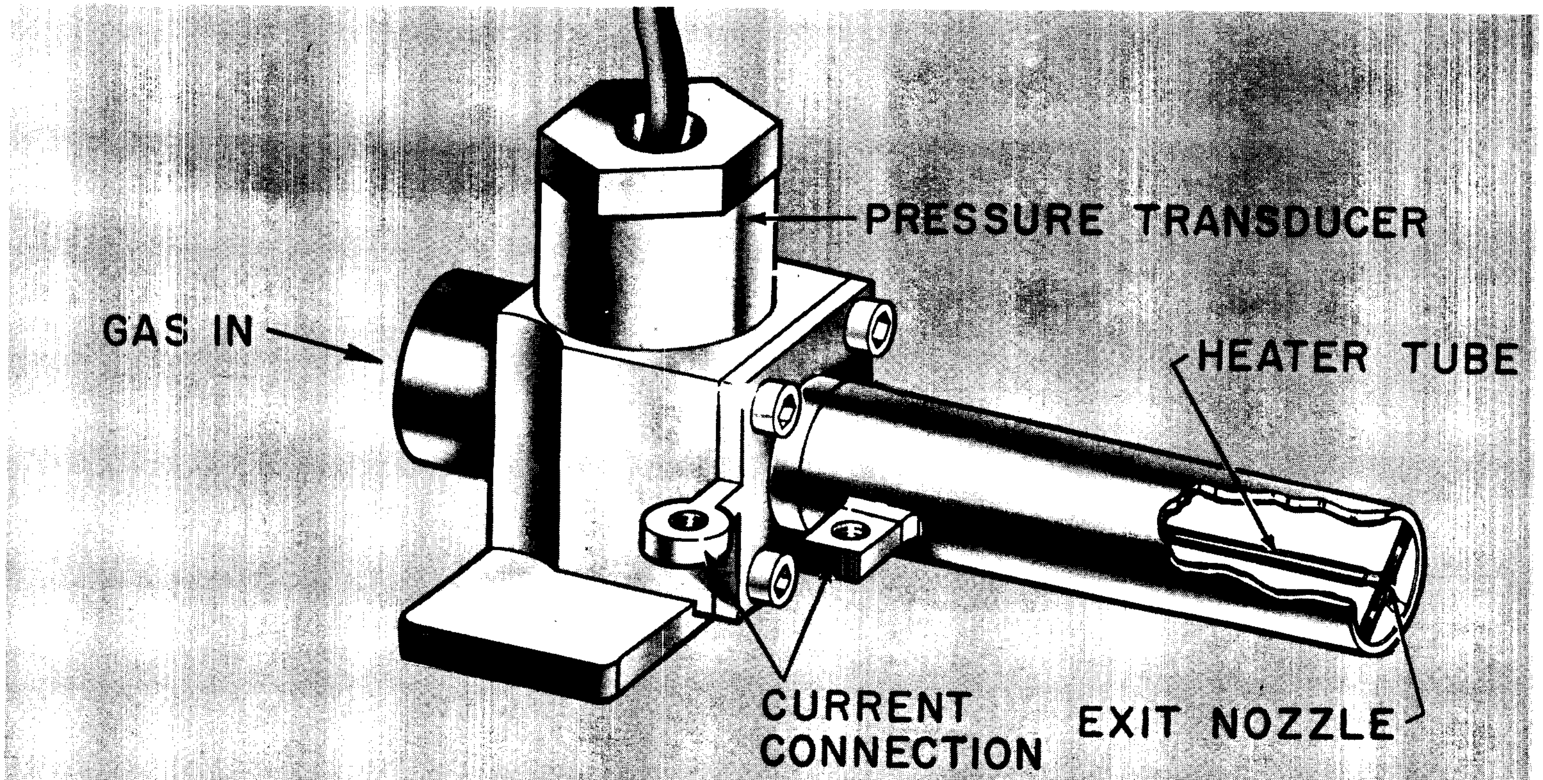
Figure 2 PHOTOGRAPH OF THE AMMONIA-FUELED RESISTOJET SATELLITE INVERSION SYSTEM



OPERATING RANGE

TOTAL POWER INPUT	0 TO 50 WATTS
MAXIMUM THRUSTOR TEMPERATURE	2000 °K
MAXIMUM OPERATING CURRENT	25 AMPERES
MAXIMUM OPERATING VOLTAGE	2 VOLTS
THRUST LEVEL	1 TO 1000 X 10^{-6} LBS
MAXIMUM SPECIFIC IMPULSE	300 SECONDS

26-3005

Figure 3 BASIC DESIGN OF THE FAST HEAT-UP RESISTOJET THRUSTOR

Figure 4 PHOTOGRAPH OF THE FAST HEAT-UP RESISTOJET THRUSTOR

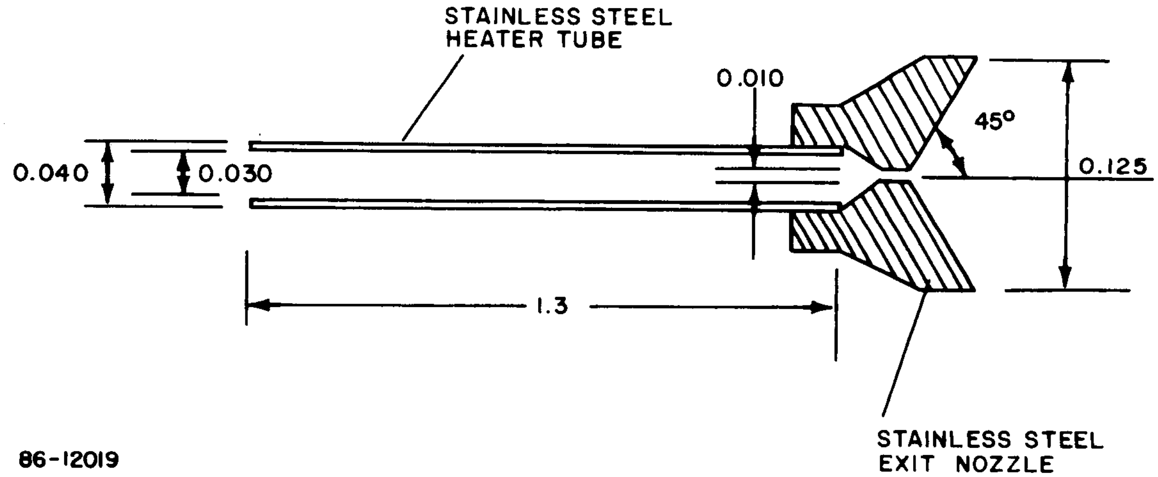


Figure 5 STAINLESS STEEL HEATER-NOZZLE ELEMENT

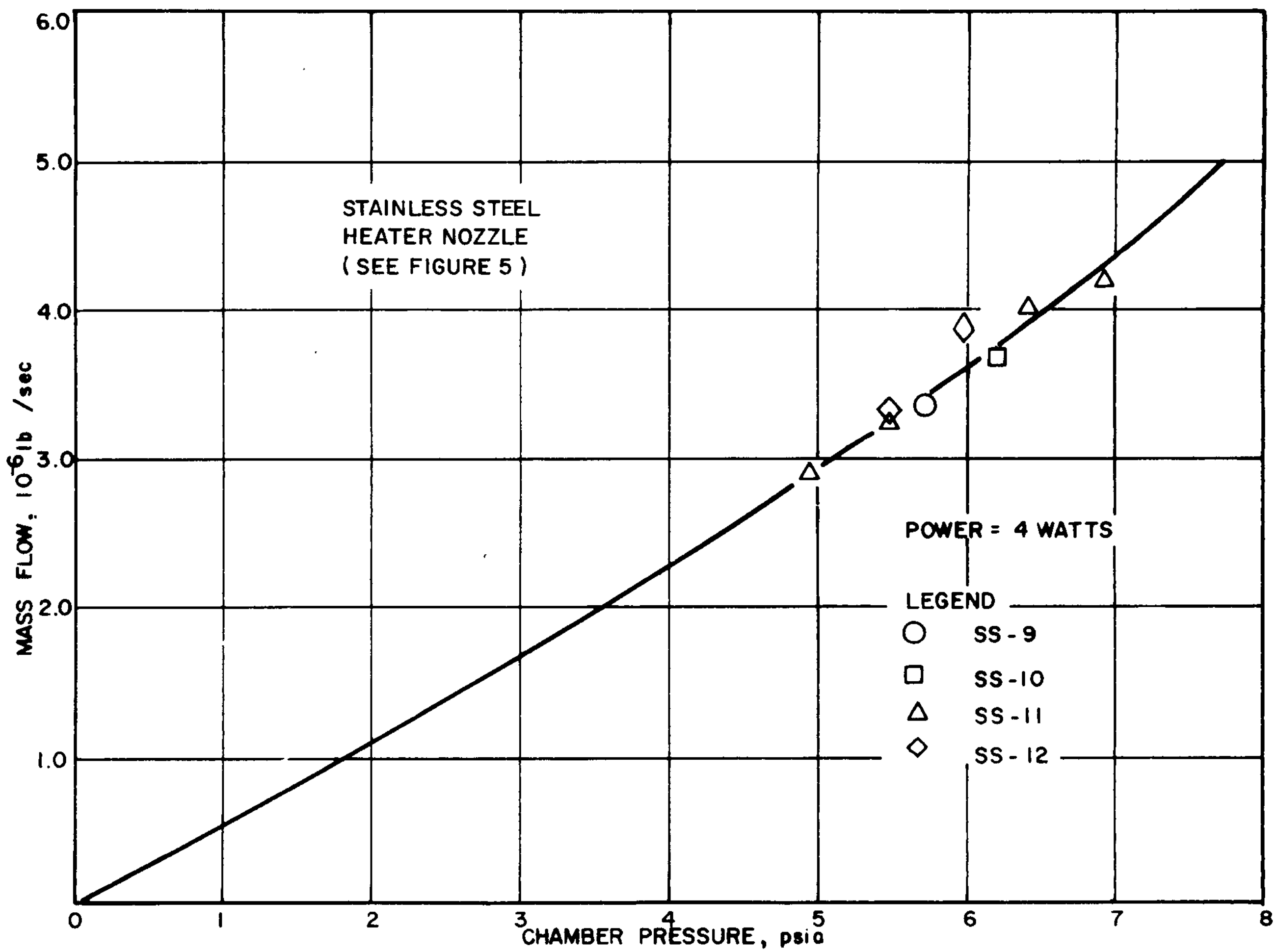


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Figure 6 RESISTOJET PROPULSION PERFORMANCE -- AMMONIA FLOW RATE VERSUS CHAMBER PRESSURE

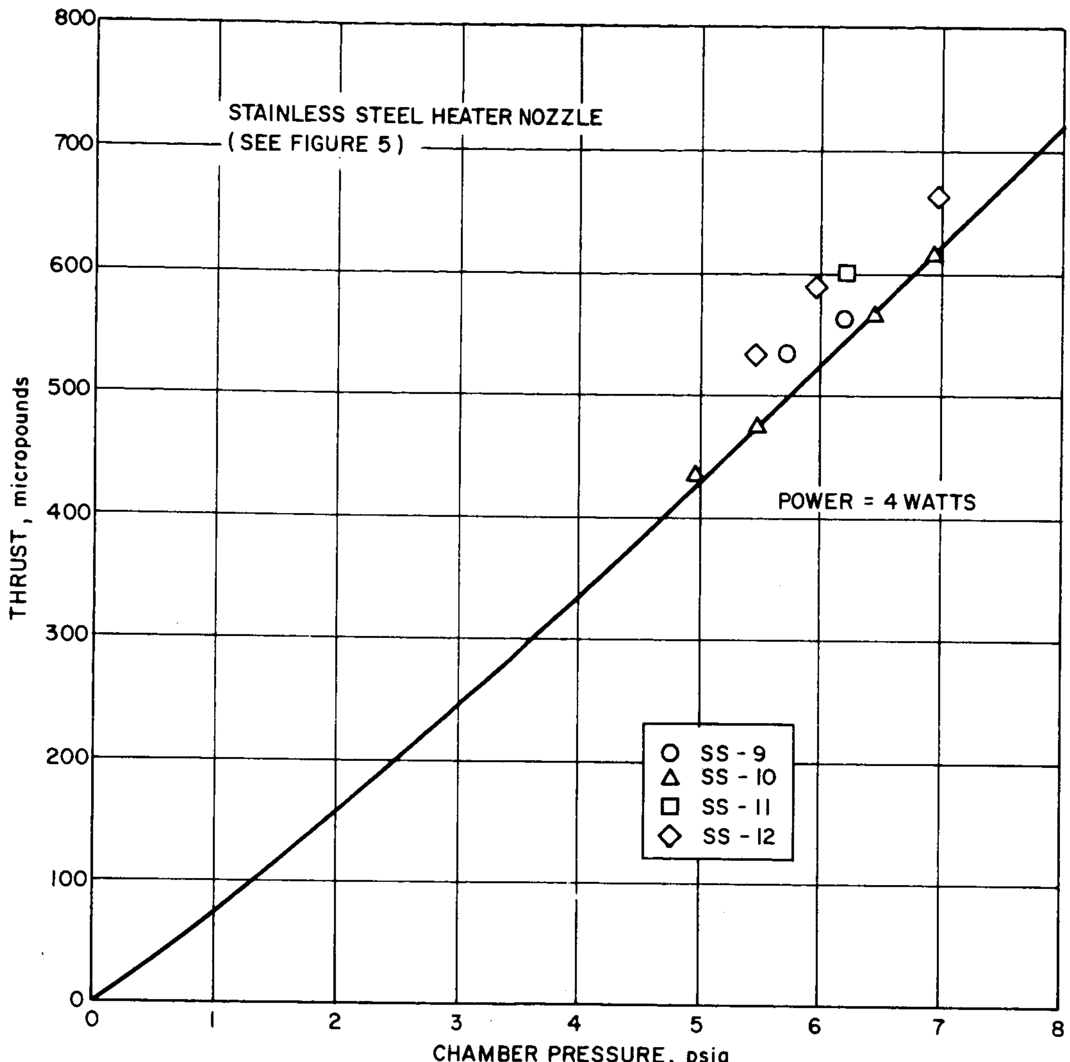

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Figure 7 RESISTOJET PROPULSION PERFORMANCE -- MEASURED ENGINE THRUST VERSUS CHAMBER PRESSURE

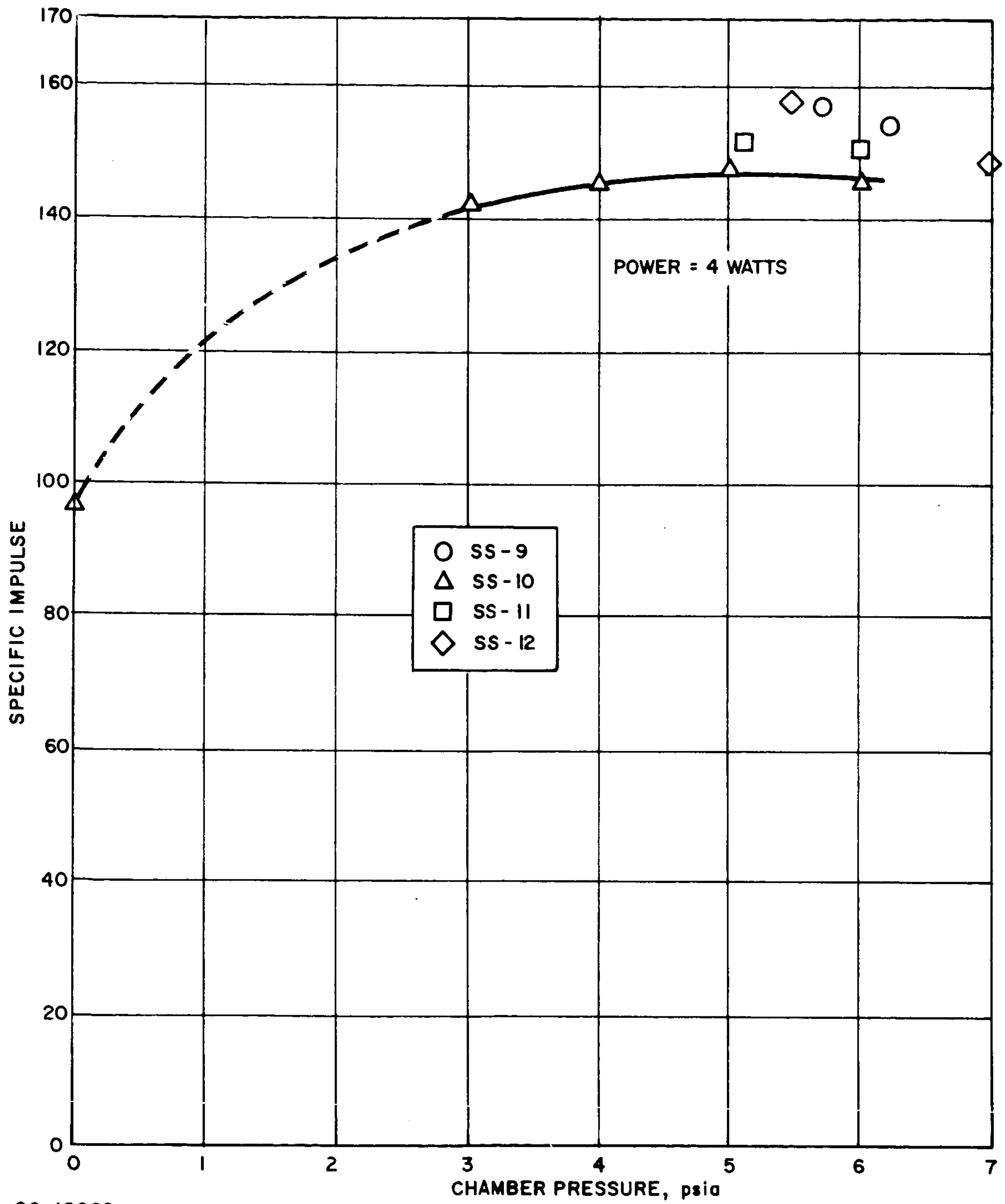

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Figure 8 RESISTOJET PROPULSION PERFORMANCE -- ENGINE SPECIFIC IMPULSE VERSUS CHAMBER PRESSURE

3. Thrustor Solenoid Valve

A Carleton Valve Model No. 1809-20 was selected as the thrustor solenoid valve. A drawing of the valve is shown in Figure 9. The valve components are compatible with both gaseous and liquid ammonia, and a single valve has been cycled at least 360,000 times, in an ammonia atmosphere, during development tests at this laboratory. The electrical characteristics for the Carleton valve are shown in Table I.

TABLE I

ELECTRICAL CHARACTERISTICS FOR THE CARLETON MODEL NO. 1809-20 SOLENOID VALVE

Current	16×10^{-3} amperes
Voltage	24 volts
Power	0.40 watt
Response Time (Open)	$\sim 10 \times 10^{-3}$ second
Response Time (Close)	$\sim 10 \times 10^{-3}$ second

C. PROPELLANT FEED AND STORAGE SYSTEM

The over-all purpose of the ammonia storage and feed system is to make available gaseous ammonia to the thrustors at the required plenum chamber pressure, and within pressure limits, as determined by allowable thrust variations. The maximum thrust variation to be tolerated for the present application is ± 10 percent. The propellant storage and feed system is also required to operate under zero gravity; the zero-gravity feature of the feed system is to be demonstrated by showing the capability of the storage tank to properly deliver propellant when in any attitude in a one-earth gravity field.

The simplest approaches to the propellant-flow regulation problem are shown in Figure 10. Mechanical regulation (Figure 10A) of the gas flow between a storage and a plenum tank is the most obvious approach; however, a series of exploratory tests on different gas regulators suggested that the lightweight models are unreliable, and that the more reliable mechanical gas regulators are too heavy. Another possible solution of the gas-flow regulation problem (Figure 10B) is to control flow of gas between the storage tank and the plenum tank by means of a flow-control valve actuated by a pressure switch which senses the plenum pressure. If the propellant flow through the flow-control valve is in a gaseous state, this method of gas plenum-pressure regulation can restrict the gas-plenum pressure deadband to the order of 1 percent. On the other hand, if the propellant flow through the control valve is a liquid, which is possible in the zero-gravity situation, the plenum pressure can overshoot

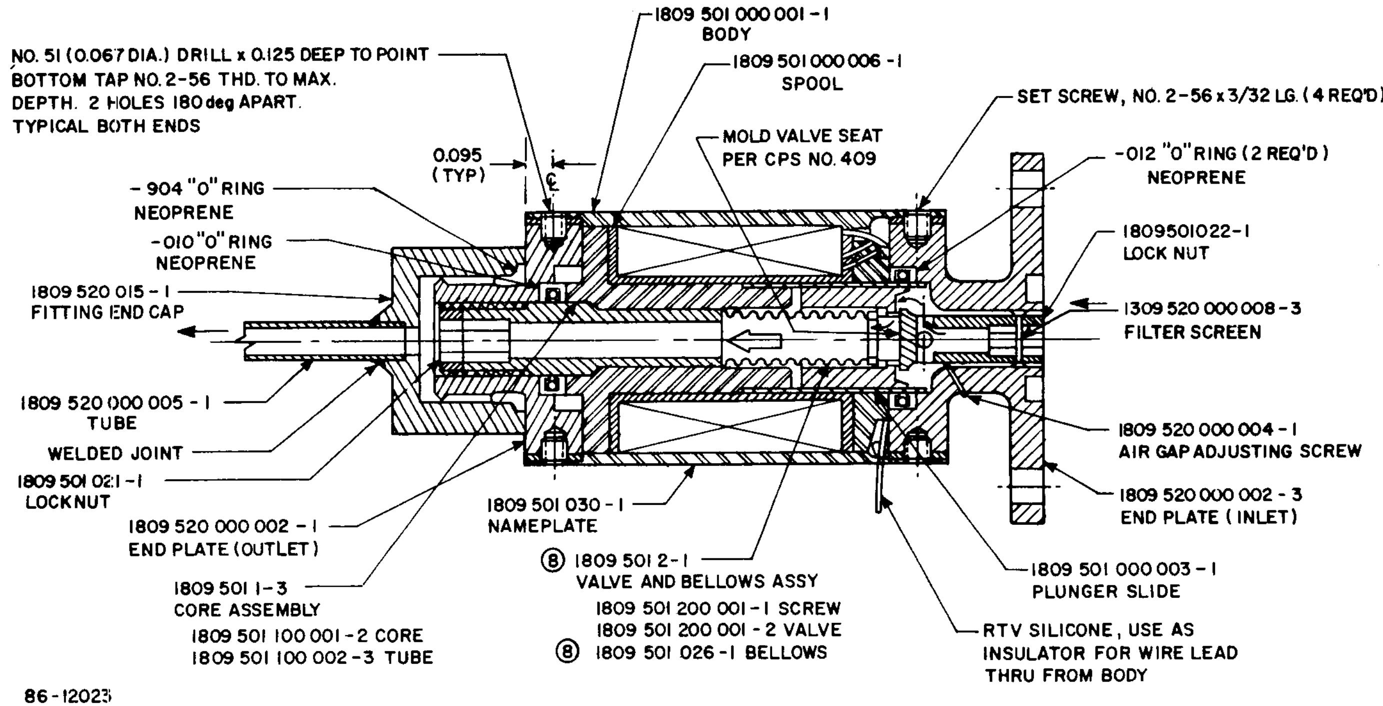
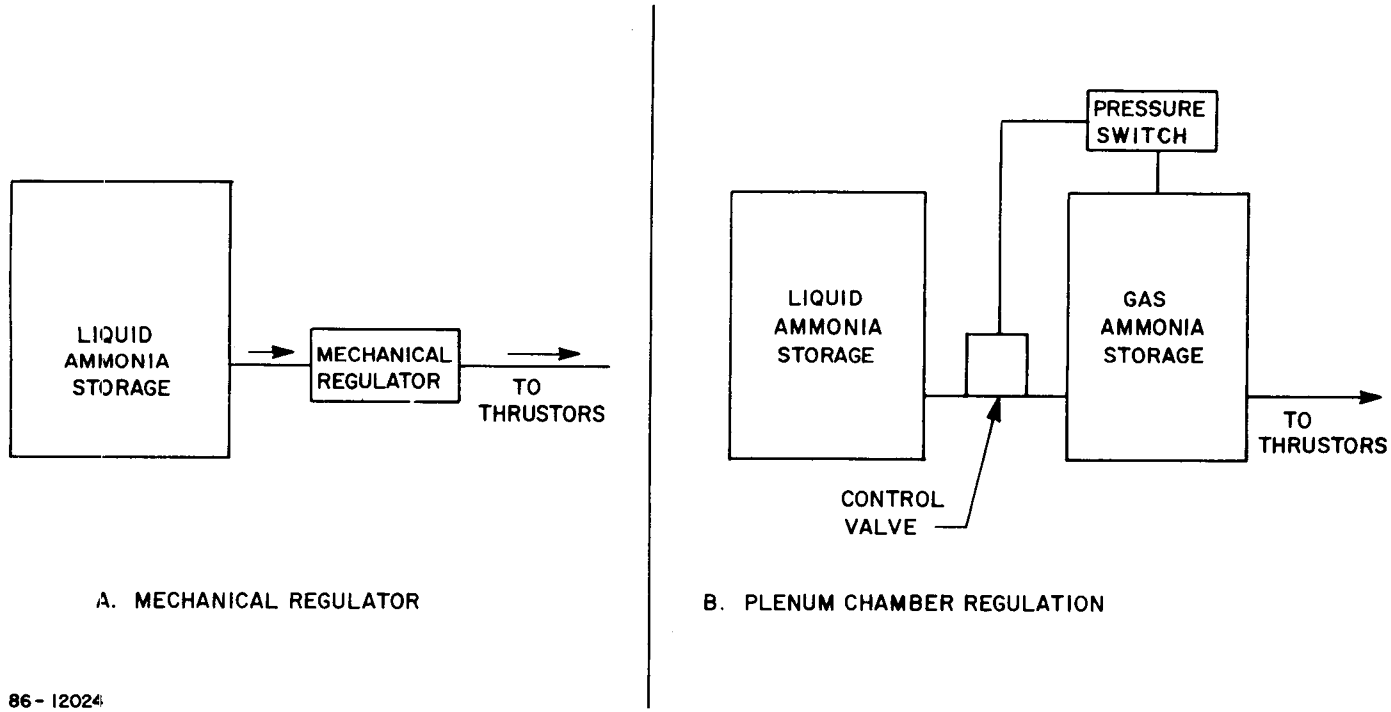


Figure 9 THRUSTOR SOLENOID VALVE -- CARLETON VALVE MODEL NO. 1809-20



A. MECHANICAL REGULATOR

B. PLENUM CHAMBER REGULATION

86-12024

Figure 10 TECHNIQUES FOR PROPELLANT-FLOW REGULATION the deadband limit by as much as 500 percent. The graphical representation of each mode of operation is shown in Figure 11, which is typical of data obtained in the laboratory.

To correct for the pressure overshoot condition when liquid flowed through the control valve,the plenum, as shown in Figure 12, was divided into two sections separated by an orifice. The pressure switch, which is connected to the flow-control valve, senses the pressure in the pre-plenum chamber. Empirically, it has been found that the use of the smaller sensing volume makes it possible to hold the plenum pressure within 1-percent limits with either gas or liquid flow through the control valve. The basic tradeoff is between valve-cycling rate and pressure regulation; the higher the pressure regulation, the greater the required valve-cycling rate. A typical plot of pressure regulation as a function of valve-cycling rate is shown in Figure 13.

The pressure switch for the ammonia feed system is manufactured by The Bristol Company of Waterbury, Conn., and is Bristol Pressure Switch-Code No. C2060-2M. The flow-control valve is the Carleton Valve Model No. 1809-20, which has been previously described.

D. POWER-CONDITIONING AND CONTROLS

The power-conditioning system for the resistojet inversion package is shown schematically in Figure 14. The power-conditioning system has been designed to operate off a negative 24-vdc power supply. The system must provide power to operate the following components: 1-2, clockwise and counterclockwise resistojet heaters; 3-4, clockwise and counterclockwise thrustor solenoid valves; 5, feed-system solenoid valves; 6, plenum-chamber pressure transducer.

The electric circuits for the resistojet heaters have been designed to convert the 24-vdc input power to the $\sim$ 1 volt required at the resistojet. To convert the input power to this level with efficiencies of the order of 80 percent, the direct-current input is converted to 10,000 Hz alternating current with an oscillator/amplifier circuit. The alternating current is then stepped down to the required level through a transformer. The basic transformer design is shown in Figure 15; it consists of a conventional wirewound configuration. The center portion of the transformer is left open to permit the resistojet thrustor assembly to be mechanically attached to the transformer assembly.

The solenoid thrustor valves are designed to operate on negative 24-volt input, and are directly connected to the input voltage. Valve-on selection is made through an either/or switch depending on the desired thrust direction.

The basic signal-conditioning circuit is shown schematically in Figure 16. The basic command input signals are counterclockwise thrustor-on and clockwise thrustor-on. The basic input signals to the telemetry encoder are in the form

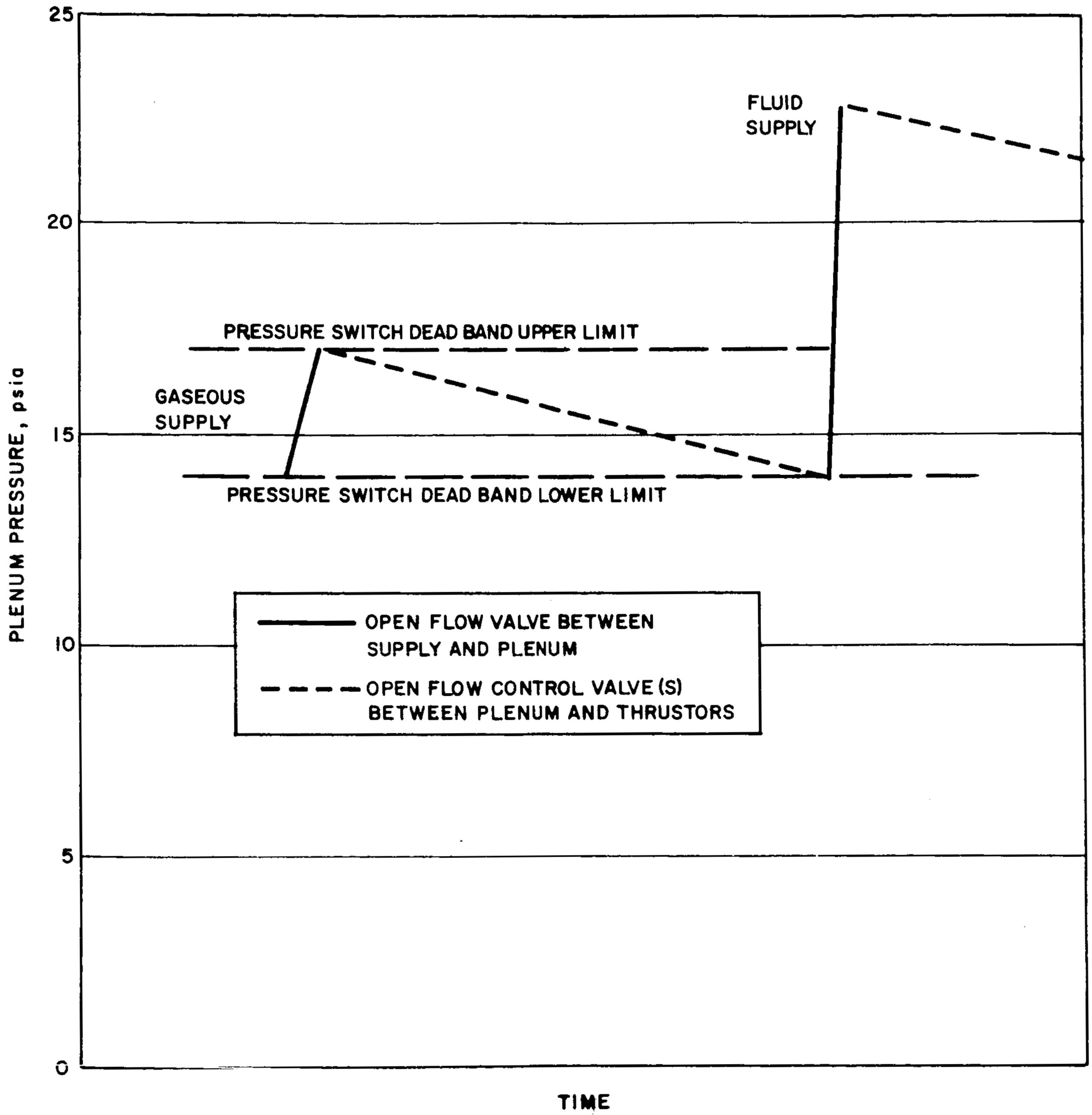


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Figure 11 PERFORMANCE OF THE AMMONIA STORAGE -- PLENUM CHAMBER GAS-REGULATION SYSTEM

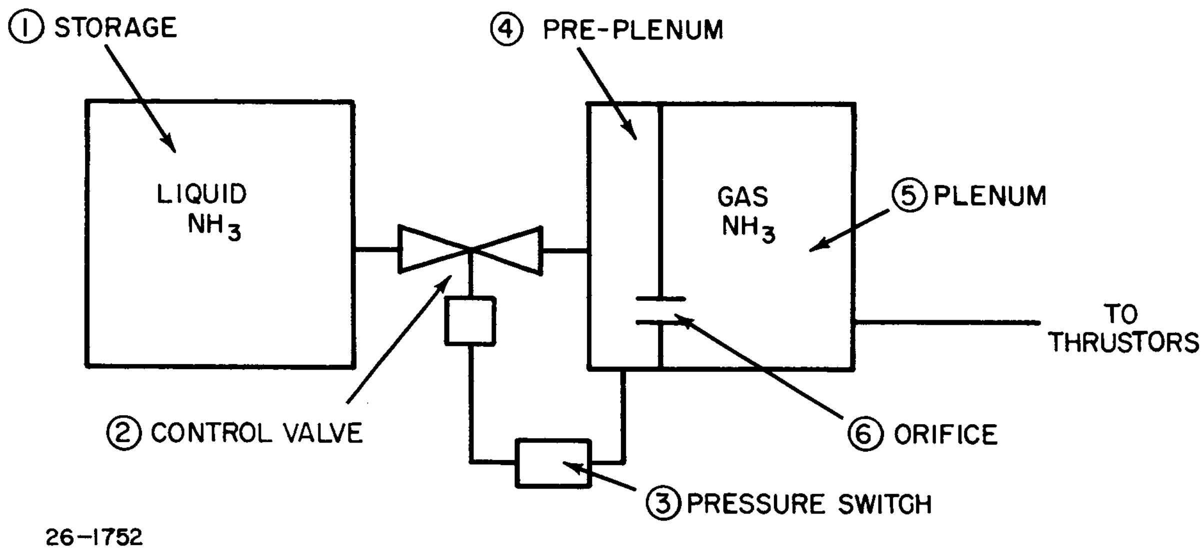

Figure 12 PROPELLANT STORAGE AND FEED SYSTEM FOR THE AMMONIA-FUELED RESISTOJET INVERSION SYSTEM

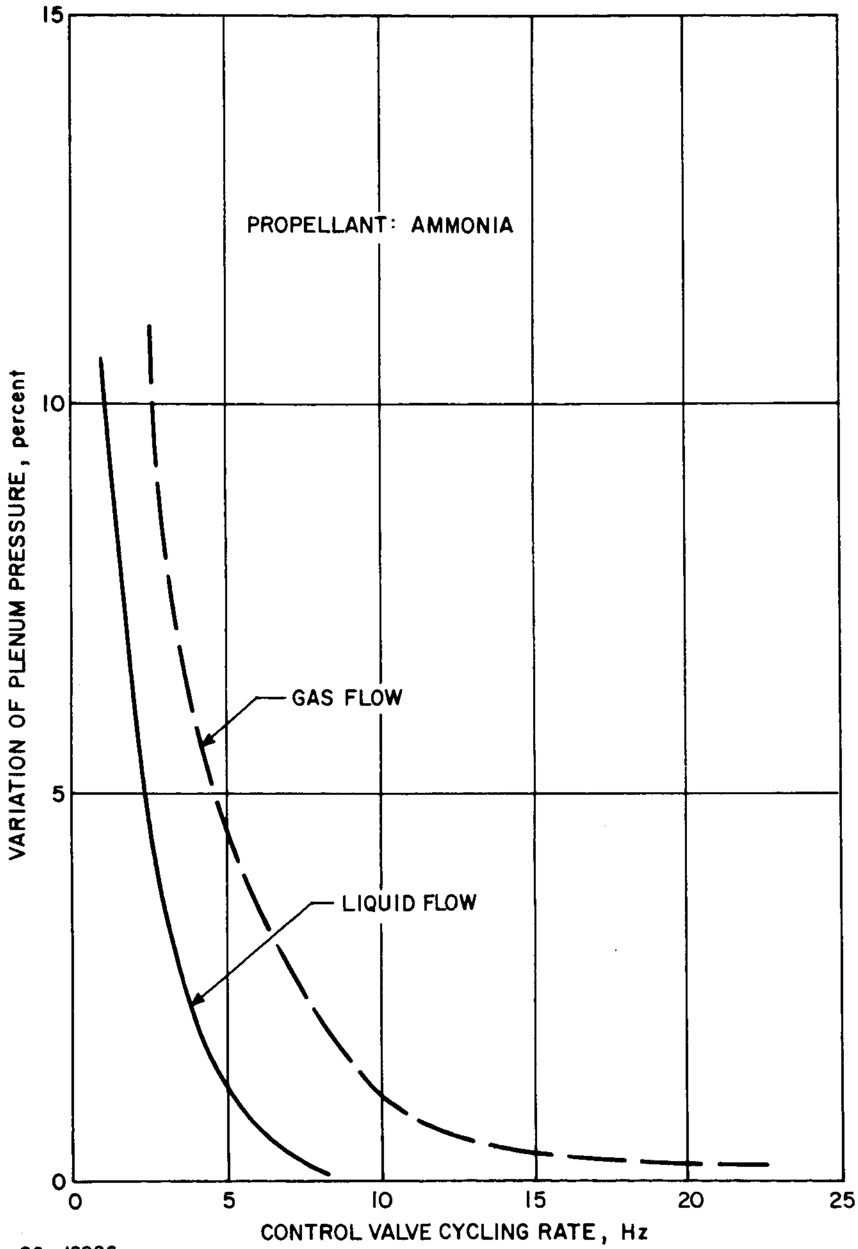

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Figure 13 PERFORMANCE OF THE GAS-REGULATION SUBSYSTEM FOR THE AMMONIA-FUELED RESISTOJET SATELLITE INVERSION SYSTEM

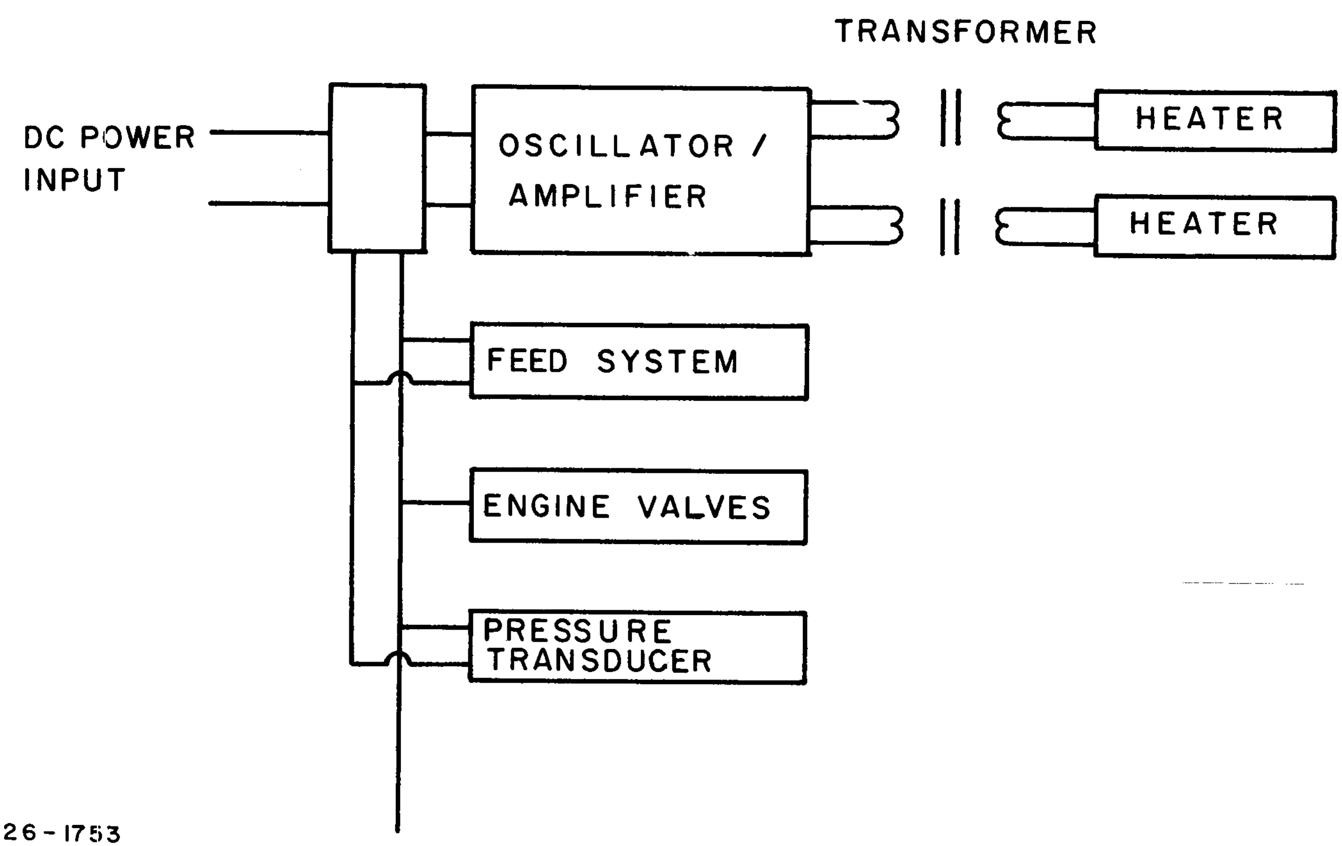

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Figure 14 POWER-CONDITIONING SYSTEM FOR THE AMMONIA-FUELED RESISTOJET SATELLITE INVERSION PACKAGE

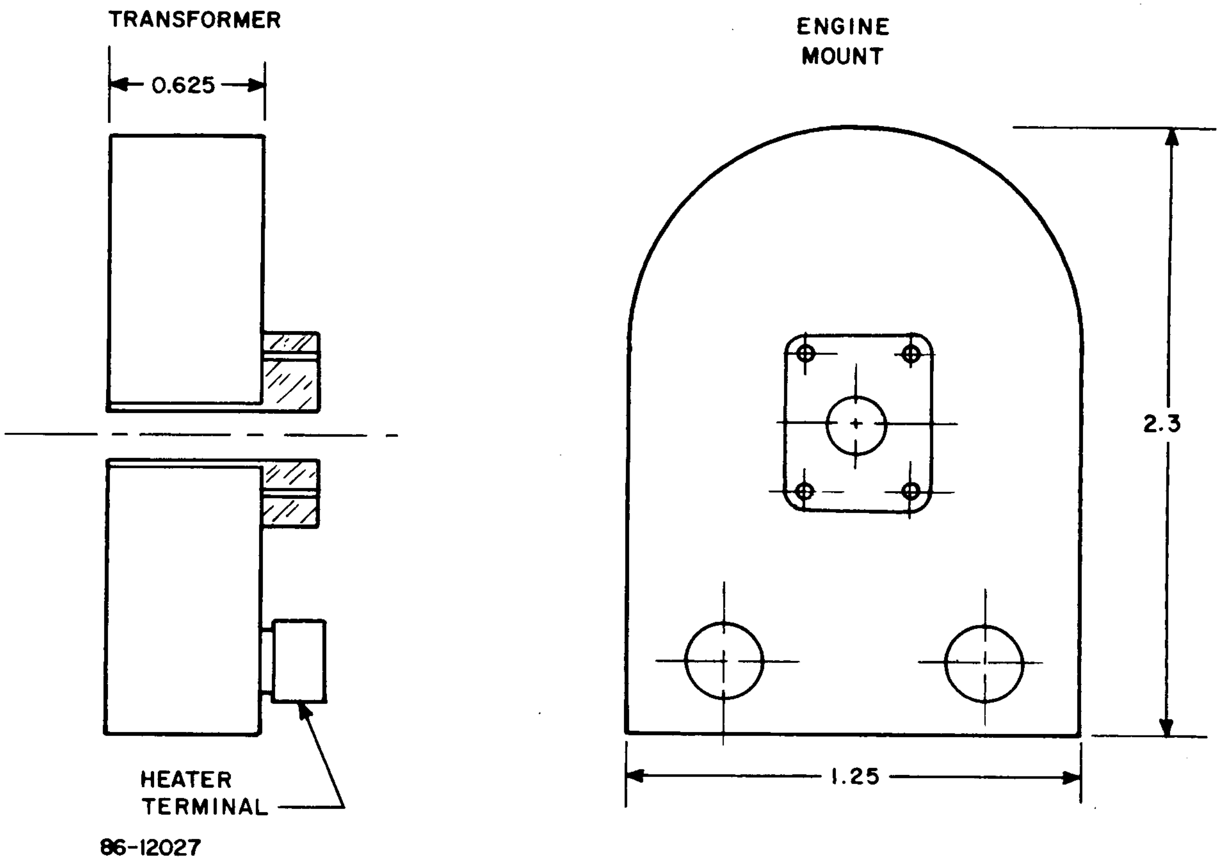

Figure 15 TRANSFORMER DESIGN FOR THE FAST HEAT-UP RESISTOJET THRUSTORS

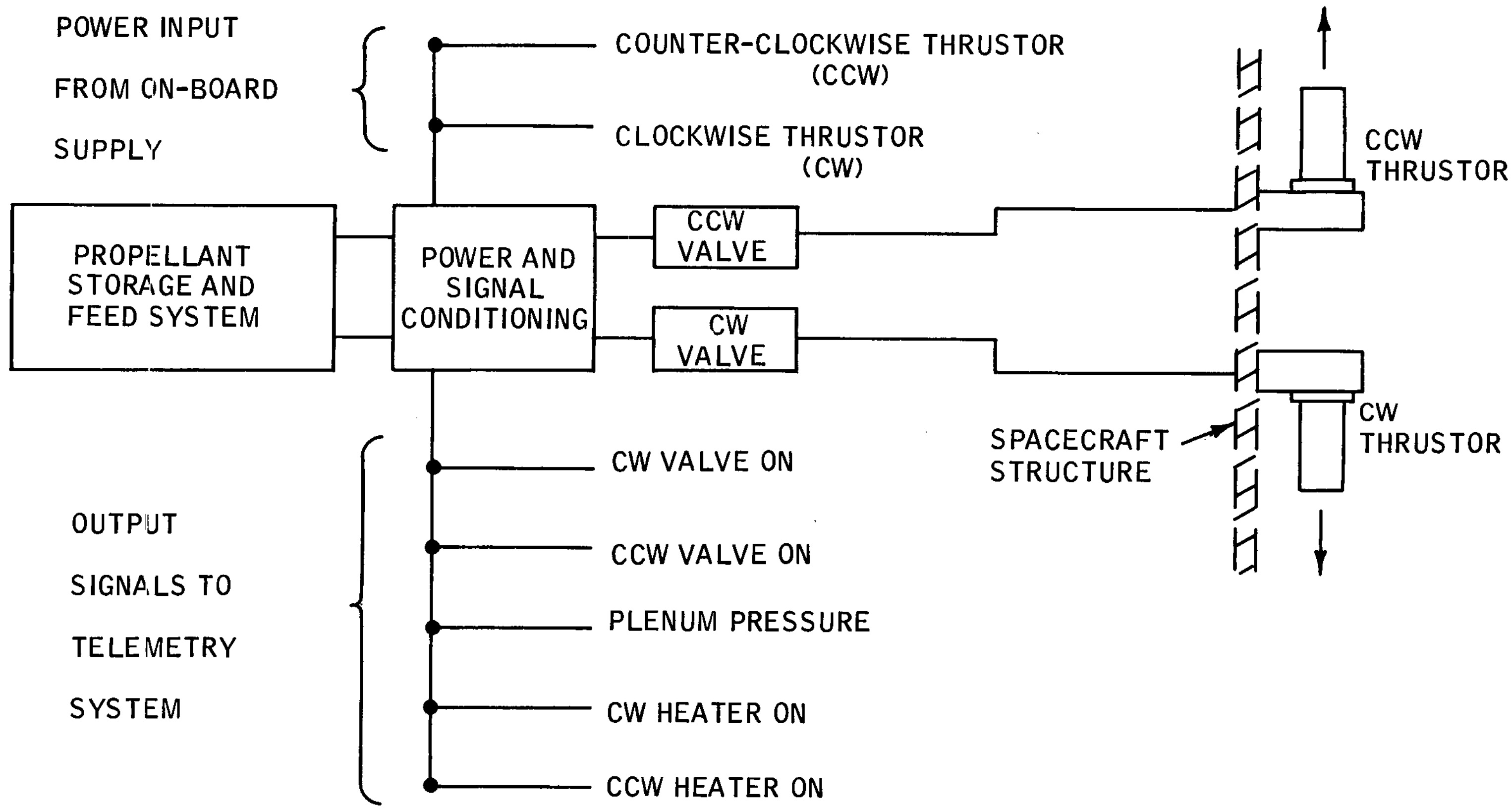

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Figure 16 SIGNAL CONDITIONING SYSTEM FOR THE AMMONIA-FUELED RESISTOJET SATELLITE INVERSION PACKAGE of 0- to 5-volt signals, having a maximum current of ± 5 microamperes and an output impedance greater than 10,000 ohms. The following data parameters are monitored: 1-2, clockwise and counterclockwise thrustor valve-on voltage; 3-4, clockwise and counterclockwise thrustor heater voltage; 5, plenum pressure; 6, propellant-valve voltage.

Figure 17 shows a photograph of the combined power and signal-conditioning subsystem designed and fabricated for the resistojet package.

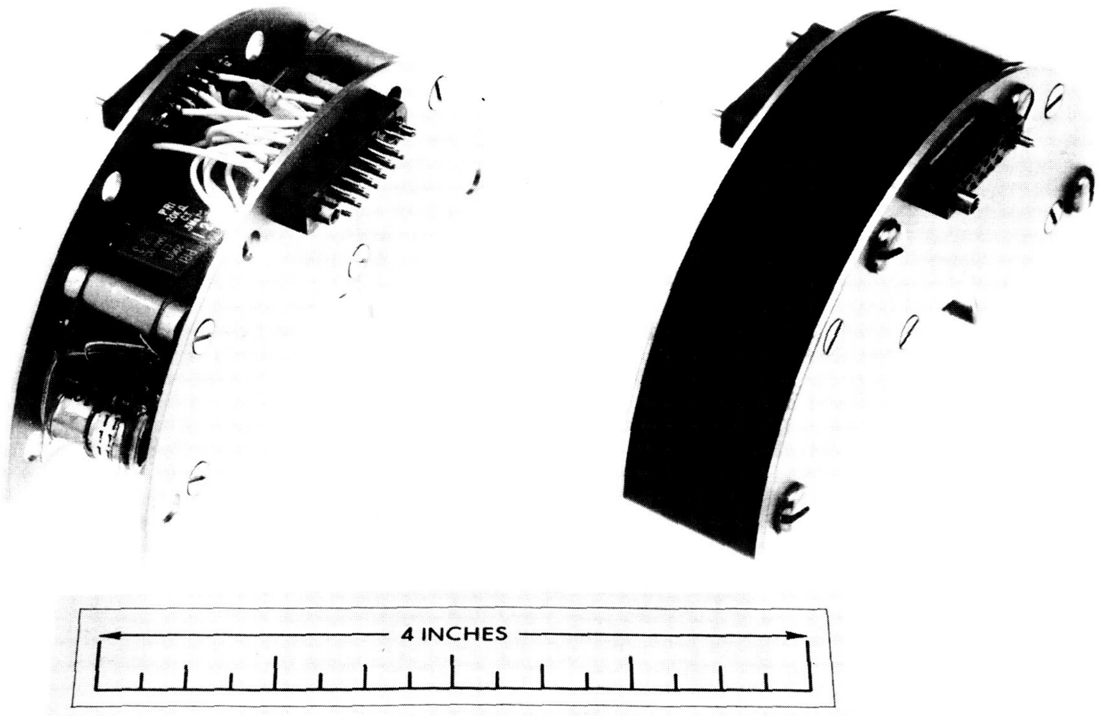

Figure 17 PHOTOGRAPH OF THE SIGNAL CONDITIONING PACKAGE FOR THE AMMONIA-FUELED RESISTOJET SATELLITE INVERSION PACKAGE

III. OVER-ALL SYSTEM PERFORMANCE

A weight breakdown for the complete resistojet thrustor package has been presented in Figure 1. As indicated previously, the system weighs 5.2 pounds empty and 6.1 pounds full. A successful 55-hour system test was carried out on the system. The results of this test are shown in Table II. During this test, the resistojet thrustors were alternately cycled for periods of 2-1/2 hours each. The test was voluntarily terminated, and no unanticipated technical problems were uncovered.

TABLE II

ENDURANCE TEST OF THE RESISTOJET INVERSION PACKAGE

Package Weight (Loaded)	6.1 pounds
Package Weight (Empty)	5.1 pounds
Performance Cycle (5 hours)	
Clockwise Engine	2-1/2 hours (on); 2-1/2 hours (off)
Counterclockwise Engine	2-1/2 hours (off); 2-1/2 hours (on)
Test Period	
Run Time	54 hours
Total Cycles	10-1/2 (+)*
Propellant Utilization	
Propellant available	0.875 pounds
Propellant remaining	0.063 pounds
Propellant used	0.812 pounds
Mean Propellant Flow Rate	
Run Time	1.94×10^5 seconds
Mean Flow Rate	4.2×10^{-6} lb/sec

*Test voluntarily terminated

TABLE II (Concl'd)

Estimated Power Balance	
Average System Power	8.3 watts
Valve and Electronics Power	3.6 watts
Power To Engine	4.7 watts
Estimated Engine Performance	
Mean Voltage	0.70 volt
Mean Current	6.7 amperes
Mean Heater Resistance	0.10 ohm
Valve Cycles	
On-Off Thrustor Solenoid Valve	11 cycles
Feed System Control Valve	48, 2000 cycles

The endurance test was carried out in a bell chamber and it was not possible to simultaneously carry-out thrust measurements. The thrustor performance data was obtained in a separate series of measurements, and has been presented in Figures 6 through 8. The estimated propulsion performance of the resistojet package is shown in Table III.

TABLE III

ESTIMATED PROPULSION PERFORMANCE OF THE RESISTOJET INVERSION PACKAGE DURING THE 50-HOUR ENDURANCE TEST

Chamber Pressure	6 psia
Thrust Level (hot)	550×10^{-6} pounds
Mass Flow Rate (measured)	4.2×10^{-6} lb/sec
Total Available Run Time	0.208×10^{6} seconds
Total Impulse Capability	115 lb-sec
Mean Specific Impulse	130 seconds

As indicated in Tables II and III the system was able to meet the required operating conditions.

IV. DIRECTION FOR FUTURE RESEARCH AND DEVELOPMENT

A. An effort should be made to flight-qualify the resistojet inversion package by subjecting it to appropriate environmental tests. Preliminary studies suggest that the test package can meet the flight-acceptance, environmental-test requirements for the ATS program.

B. A study should be made of the feed system modifications required to permit the resistojet inversion package to operate over the thrust range from 1 to 1000 micropounds. Preliminary work suggests that the thrust range can be varied by installing different length capillary tubes between the plenum chamber and thrustor solenoid valve. These speculations should be confirmed by measuring the propulsion performance of the resistojet package on a direct thrust measurement system.

APPENDIX

APPENDIX A

LIST OF WORKING DRAWINGS FOR THE RESISTOJET SATELLITE INVERSION SYSTEM

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